Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

CANMET
Canada Centre for Mineral and Energy Technology
Centre canadien de la technologie des minéraux et de l'énergie

CHARACTERIZATION AND VISCOSITY MEASUREMENTS OF SLAGS FROM PULVERIZED COALS IN A PILOT-SCALE RESEARCH BOILER

D.H.H. Quon, S.S.B. Wang and T.T. Chen
Mineral Processing Laboratory

February 1983

This document is an unedited interim report prepared primarily for discussion and internal reporting purposes. It does not represent a final expression of the opinion of the Canada Centre for Mineral and Energy Technology (CANMET)

Ce document est un rapport provisoire non-révisé et rédigé pour discussion et pour fin de documentation interne. Il ne représente nullement l'expression définitive de l'opinion du Centre canadien de la technologie des minéraux et de l'énergie (CANMET)

Project ERP-4.3.0.7.02
Low-Grade Coal in Utility Boilers

ENERGY RESEARCH PROGRAM
MINERAL SCIENCES LABORATORIES
DIVISION REPORT ERP/MSL 83-18 (IR)

MICROMEDIA

CHARACTERIZATION AND VISCOSITY MEASUREMENTS OF SLAGS FROM PULVERIZED COALS IN A PILOT-SCALE RESEARCH BOILER

by

D.H.H. Quon*, S.S.B. Wang** and T.T. Chen***

ABSTRACT

Samples of coal-ash slags were characterized using optical and scanning electron microscopy, differential thermal and thermogravimetric analysis and X-ray diffraction. The results show that the slags contain essentially a glassy phase with minor crystalline phases such as mullite, cristobalite and quartz.

Viscosity of the slags was measured and compared to the calculated viscosities. A significant difference in values was obtained between these two techniques.

Research Scientists, *Ceramic Section, **Non-metallic Minerals Section, ***Mineralogy Section, Mineral Processing Laboratory, Mineral Sciences Laboratories, CANMET, Energy, Mines and Resources, Canada, Ottawa.

CONTENTS

	Page
ABSTRACT	i
INTRODUCTION	1
EXPERIMENTAL	1
Materials	1
Characterization	2
RESULTS AND DISCUSSION	4
Differential Thermal and Thermogravimetric Analyses	5
SINTERING	5
Viscosity Measurements	7
CONCLUSIONS	9
RECOMMENDATIONS	9
ACKNOWLEDGEMENTS	9
REFERENCES	25

FIGURES

Page

Fig. 1 - Schematic arrangement of viscometer and furnace set-up for viscosity measurement 10

Fig. 2 - Concentric cylinder viscometer 11

Fig. 3 - XRD patterns for the slag samples and the slag sample heat treated (A613-81-1130-4) 12

Fig. 4 - DTA and TGA thermograms for slag sample A464-81 13

Fig. 5 - DTA and TGA thermograms for slag sample A519-81 13

Fig. 6 - DTA and TGA thermograms for slag sample A613-81 14

Fig. 7 - XRD pattern for the as-received slag samples (A613-81 and A519-81), heat treated slag sample (A613-81-1130-4) and synthetic samples (S1-1285-2, (S1-1235-3, S2-1337-2 and S3-1260-2) 15

Fig. 8 - SEM micrograph of synthetic sample sintered at 1377°C for 2.5 h 16

Fig. 9 - SEM micrograph of synthetic sample sintered at 1390°C for 2.5 h 16

Fig. 10 - Viscosity as a function of temperature for the slag samples 17

Fig. 11 - Calculated viscosity-temperature relationship for the slag samples 18

TABLES

		Page
1.	Chemical composition of the slag samples	19
2.	Thermal behaviour of slag samples determined by the ASTM testing method	20
3.	Chemical composition of the synthetic samples	21
4.	Viscometer calibration equations	22
5.	Phase characteristics of the slags	23
6.	Mass of silica, alumina and mass ratio of silica/alumina of the slag samples	24

INTRODUCTION

Fireside fouling of boiler heat transfer surfaces reduces boiler efficiency and availability. During the combustion process, the extreme temperature rise can either transform or recombine the mineral matter in coal into new phases. These new mineral phases can remain as solids and pass through the boiler as fly-ash or, for the less refractory phases, they can melt and become a liquid or liquid-solid mixture, which in turn may stick to the heat transfer surfaces in the boiler.

Several parameters have been used to classify the high temperature behaviour of coals using the ASTM ash cone melting method (1-4). This is still a standard technique used in many countries and it provides the basis for specifying the fusion characteristics of a large part of the coal sold for steam generation in this country. It is recognized that the tests have limited usefulness in predicting the behaviour of coal ash at high temperatures as this test gives poor agreement with operational experience. From a consideration of the slagging mechanism it is apparent that the measurement of molten ash viscosity would provide a better test method.

As part of the CANMET effort to study the mechanism of fouling and slagging of Canadian coals, slags produced from pulverized coal in a pilot-scale boiler of the Combustion Research Laboratory, CANMET, were characterized and their flow characteristics at high temperatures were determined using a viscometer.

Phase I of this work involved a preliminary examination of the coal slags derived from western Canadian coals; Phase II will include coal slags derived from eastern Canadian coals. It is anticipated that the compositional differences in these coals would provide some insight as to the mechanism that causes both fouling and slagging in the boilers.

EXPERIMENTAL

MATERIALS

The boiler slags were produced from western Canadian coals by the Canadian Combustion Research Laboratory (CCRL) of CANMET in 1981 from the CCRL pilot boiler. The chemical compositions of the slag samples and their

thermal behaviour are given in Tables 1 and 2 respectively.

In brief, slag A464-81 was produced by firing a medium volatile bituminous coal. The slag is highly refractory. The parent coal contained approximately 30% ash (mineral matter) initially and was reduced to 16% ash by washing prior to firing. Slag A484-81 was produced from the same coal but fired under different conditions. Slag A517-81 was obtained by firing a washed coal containing 11% ash from the same locality.

Slag A592-81 was produced from firing a medium volatile bituminous coal with approximately 15% ash. Slag A613-81 was produced from the same coal under different firing conditions.

Both slag A519-81 and slag A545-81 were produced from a low volatile bituminous coal with approximately 20% ash, but fired under different conditions; the former is slightly oxidized.

CHARACTERIZATION

The as-received slag samples were characterized by optical and scanning electron (SEM) microscopy and X-ray diffraction (XRD). The chemical composition of the slags was determined using the electron microprobe (EMP).

Differential thermal (DTA) and thermal gravimetric (TGA) analyses were used to determine the thermal reactions that occur during heating.

To understand the reactions and phase formation of the various chemical constituents at high temperatures, attempts were made to prepare synthetic samples similar to the slag compositions. The compositions of the synthetic samples, containing silica, alumina and ferric oxide with minor additions of calcium and potassium oxides, are given in Table 3. The starting materials used were analytical grade silia, alumina, ferric oxide, potassium and calcium carbonates. Appropriate amounts of the above materials were weighed, mixed, and calcined at 1000°C. The calcined samples were then pressed into pellets having a diameter 1 cm by 0.5 cm high in a die using a uniaxial pressure of 45 MPa. The pellets were subsequently sintered in a resistance furnace at different temperatures and time durations. Phases formed in the sintered pellets were characterized by XRD technique.

Viscosity measurements were carried out on the as-received slag samples using a high temperature viscometer.

The viscometer used was based on similar equipment developed by Toguri et al. (5) to study metallurgical slag.

The schematic arrangement of the furnace used for the viscosity measurements is shown in Fig. 1. A molybdenum crucible is used for containing the molten slag. The advantage of using molybdenum is its high refractoriness and low tendency to react with the slag at high temperature. The disadvantage of using molybdenum is the inability for the crucible to stand up in an oxidizing atmosphere. The molybdenum crucible is placed inside of an alumina crucible and zirconia beads are tightly packed between the two to provide thermal insulation and to secure the molybdenum crucible. An alumina tube lined with molybdenum foil is used as a heat shield. Molybdenum foil is placed directly on top of the heat shield to serve as a heat reflector. The whole assembly is set inside a silica tube (75 mm ID x 265 mm long), which is fitted snugly inside the induction coil. A small silica tube attached to the main silica tube at an angle of 45 degrees serves as a viewing port for temperature measurements using an optical pyrometer. A gas inlet is fitted on the top aluminum plate to allow argon to flow into the furnace and prevent oxidation of the molybdenum crucible. Both the upper and bottom aluminum plates are tightly fitted onto the silica tube using "O" ring seals to prevent excess gas loss. The viscometer spindle is introduced into the furnace through the opening in the top aluminum plate. Heating of the furnace is achieved by coupling the molybdenum crucible to the induction generator. The induction generator is capable of delivering up to 30 kW.

During the experimental runs, plasma formation was observed due to ionization of the argon gas. To supress the plasma, 1 vol % of nitrogen was mixed with 99 vol % of argon. With this gas mixture the molybdenum wares show no sign of oxidation up to temperature above 1700°C.

The viscometer system used for this study is essentially a rotating cylindrical type. The viscometer bob (innter cyliner) dimension is shown in Fig. 2. The bob is constructed of two parts, the main cylindrical body and the spindle. The two sections are tightly fitted together. Also shown is the change in diameter of the spindle above the main cylinder to prevent the liquid from creeping up the shaft. The dotted line in Fig. 2 shows the position of the bob in the crucible during the viscosity measurements. The viscometer is calibrated with the bob at this fixed level inside the crucible.

The torque meter incorporated in this viscosity measurement apparatus is a Brookfield Rheolog type viscosity transmitter, Model RVG, equipped with an eight-speed transmitter. Details of the transmitter construction are given by Van Wazer et al. (6). The RVG model is equipped with a back-sensing fluidic flapper nozzle arrangement to convert the spring torque to an air pressure (24 to 165 cm of water, -2344 to 16138 Pa) in a complete linear fashion. The output from this rheolog sensing head (transmitter) is fed into a pneumatic-to-electric transducer giving an output of 0-10 mV, which is in turn fed to the recorder.

The viscometer system was calibrated using Brookfield silicone standard oil of known viscosity. The silicone oils were chosen because they possess Newtonian characteristics and readily wet the surfaces of the molybdenum bob and crucible.

The crucible was filled with 50 mL of calibration fluid and was partially immersed in a constant temperature water bath at 25°C. The bob was then introduced into the crucible, spindle rotation was initiated, and the signal from the transmitter was recorded in term of millivolts for a given spindle velocity.

The data obtained from the standardization procedure were treated by a least-squares-fit computer program, which generated a linear relationship between the viscosity measured and voltage output of the torque meter at the various available rotational velocities, as shown in Table 4.

RESULTS AND DISCUSSION

Megascopic examination of the slag samples indicated that the major phase they contain is glass. In order to examine these samples in more detail, polished sections were prepared for microscopic examination.

In the polished sections, in addition to the glassy phase, crystallites were also observed. It was impossible to establish the identity of the crystallites using the optical microscope. Hence the samples were examined by X-ray diffraction (XRD) analysis. The 'd' spacings from the diffraction patterns were measured, and the phases in these samples were identified. Typical diffraction patterns are shown in Fig. 3 as obtained from the densitometer trace of the XRD patterns. The diffraction peaks are ascribed to mullite, cristobalite and quartz.

Scanning electron microscopy (SEM), energy dispersive X-ray (EDXR) and electron microprobe analysis (EMPA) were also used for the phase characterization. Details of the SEM, EDXR, and EMPA results are described in a separate report (7).

With the combined analytical techniques it was possible to identify the various phases in the slag and the results are given in Table 4. In addition to the glass, mullite, cristobalite, and quartz, other phases found in sub-quantity included magnetite, hematite, feldspar, rutile, FeSi and silicates of Mg, Ca, and Al.

Electron microprobe analysis on the slags reveals that the chemical composition varies within individual samples. Table 1 gives the averaged chemical composition of the slags as determined by the EMPA.

DIFFERENTIAL THERMAL AND THERMOGRAVIMETRIC ANALYSES

The DTA and TGA results of the samples examined are given in Fig. 4 to 6. The TGA results show that most of the samples tend to show a mass loss varying from 0.5 to 1.75 mass % at temperatures between 350 and 500°C with the exception of one sample (A519-81), which shows a slight mass gain. The DTA results show either a single peak or a combination of several exothermic peaks at temperatures below 500°C. It is rather difficult to assign the various reaction peaks resulting from the formation and decomposition of different phases in the slag due to heating. By correlating both DTA and TGA data, it can be postulated that the exothermic reactions occurring below 500°C are due to the oxidation of the carbon residue.

It can be concluded that no major reaction of the constituents in the slag occurred below 1000°C.

SINTERING

To determine the chemical reactions of the various constituents in the slag, attempts were made to sinter some of the as-received samples. It was anticipated that the sintering process would promote the recrystallization of the glass phase and thus provide some insight into the phase formation due to the heating effect.

Two of the slag samples (A-613-81 and A519-81) were selected for the sintering study. The samples were pulverized to less than 100 μm. Pellets, 5 mm high by 1.25 cm in diameter, were made using a die at a pressure of 450 MPa. The pellets were then sintered in a Globar furnace at different temperatures and for different time periods. The sintered pellets were characterized by XRD, optical and SEM microscopy.

XRD patterns of the sintered slags fired at temperatures from 1130 to 1337°C are shown in Fig. 7 and are compared with those of the unheated slag samples. The XRD patterns for the sintered pellets are identical to those for the as-received slag samples. The phases detected are mullite, cristobalite and glass. It can be concluded from this experimental work that sintering of the slag samples did not induce the recrystallization of the glass phase.

Due to the excessive amount of glass phase present in the slag samples, as well as in the sintered slag samples, it was rather difficult to establish the crystallization sequence of the various phases formed during the coal combustion process. The chemical analyses of the coal slag samples, shown in Table 1, indicate that the major chemical components in the slag are silica and alumina. These two components have a mass ratio varying from 1.98 to 2.71. Other chemical constituents in the slag are iron, calcium and potassium oxides. It may be considered as a ternary system Al_2O_3-SiO_2 -XO (X = Fe, Ca, K). The system can be further simplified if one assumes that the iron oxide formed partial solid solution with alumina or crystallized as spinel or hematite. In other words, the reaction of the iron oxide and the other constituents in this simplified ternary system is minimized. To obtain some qualitative means of interpreting the thermal behaviour of the mineral matter in coal, synthetic samples were prepared. The compositions of the synthetic samples are given in Table 3. Pellets containing various amounts of alumina, silica, calcia and potassium oxide were sintered at 1258, 1325, 1337, 1355 and 1390°C for a period of two hours. The phases formed in the sinters were characterized by the XRD technique. The results indicate that the phases are similar to those for the as-received slag samples and comprise mullite, quartz and cristobalite (Fig. 7). Alumina was observed in the sinters: because the sintering tests were conducted at temperatures below 1400°C, some of the alumina was not fully reacted with the other constituents in these synthetic samples. In all the sintered samples a progressive

development of the liquid phase with increasing sintering temperature was observed. The liquid first appeared at 1325°C and it increased with increasing temperature. A higher proportion of liquid phase was observed in the samples richer in CaO. It appears that some of the CaO was reacted with alumina and silica to form a calcium alumino-silicate phase that melts at a considerably lower melting temperature than quartz, cristobalite and mullite. The presence of mullite, quartz and cristobalite indicates that the compositions of the sinters lie within the mullite field in the simplified ternary system. It was not possible to postulate the effect of the potassium oxide in the development of the liquid phase as this component partially evaporates during heating.

SEM micrographs of the sintered synthetic pellets are presented in Fig. 8 and 9. The micrographs show three distinct phases. The matrix phase is glass having a composition of alumino-silicate with trace of Fe, Ca and K. The Si concentration is higher than Al. The light grey to dark grey phases are silica, and the crystallites are mullite.

VISCOSITY MEASUREMENTS

Among the slag samples provided by CCRL, only three were of sufficient quantity for viscosity measurements. The slags were ground to minus 200 mesh and heated at 1000°C to remove moisture and carbon residue. About 130 to 140 g of sample were required to fill the molybdenum crucible. The calcined samples were uniaxially compacted in a die using a pressure of 20 MPa. Discs 3 cm in diameter by 2 cm high were made and loaded into the crucible with additional finely ground slag packed into the space in between the discs and the inner crucible wall. The sample and crucible were placed inside the induction furnace for viscosity measurements.

The viscosity versus temperature for different slags are plotted in Fig. 10. Slag A613-81 shows a sharp decrease in viscosity at about 1450°C. The temperature corresponding to this transition is defined as the temperature of critical viscosity. The critical viscosity temperature for the two other slags is not apparent in the Figure because the viscosity measurements were conducted at temperatures exceeding the critical viscosity temperature. However, because of the small difference in compositions of these slags, it is unlikely that the critical viscosity differs greatly. It may be assumed that the critical viscosity temperature for these samples falls within the range of 1400 to 1500°C.

The results in Fig. 10 show that viscosity decreases as temperature increases. The lowering of the viscosity is due to the thermal agitation caused by an increase of temperature, which loosens the silicate network. The SiO_2/Al_2O_3 mass ratio (Table 6) in the slag increases and the viscosity decreases at a constant temperature. The SiO_2/Al_2O_3 ratio seems to have a greater influence on viscosity than CaO and Fe_2O_3, due to the high concentration of silica and alumina present in the samples.

The viscosity of coal slags has been investigated by other workers (8, 9, 10, 11). More recently Watt and Fereday showed the influence of temperature on viscosity for various British coal ashes (11). Based on their viscosity measurement work, an empirical formula was developed to calculate the viscosity of coal ash with a known chemical composition. The formula is as follows:

$$\log \eta = 10^7 \, m/(t-150) + d$$

where η is viscosity in poises, t is the temperature in degrees C and m and d are constants calculated from the compositions of the coal ashes.

By using a regression analysis, they found that:

$$m = 0.00835 \, SiO_2 - 0.00601 \, Al_2O_3 - 0.109$$

where

$$SiO_2 + Al_2O_3 + Fe_2O_3 + CaO + MgO = 100 \text{ and } d = 0.0415SiO_2 - 0.0192Al_2O_3 - 0.0276Fe_2O_3 + 0.016CaO - 3.92.$$

According to Watt and Fereday (11), the calculated viscosity values show excellent agreement with the measured values for a wide range of the British coal ashes. Using the above formula, the viscosities of the three present slag samples were also calculated and the results are plotted in Fig. 11. As can be seen, the calculated viscosities for these samples are significantly higher than the measured values by multiples of 2 to 11. In addition, the calculated viscosities show no significant change with respect to the variation in SiO_2/Al_2O_3 ratio in these samples as compared to the measured viscosities in which a noticeable change was observed in viscosity-temperature relationship with respect to compositional variation.

CONCLUSIONS

Seven coal-ash slags provided by CCRL, CANMET, have been characterized.

The results show that these samples consist largely of a glassy phase of aluminosilicate composition with minor crystalline materials such as mullite, cristobalite, quartz and a trace of spinel.

DTA and TGA between room temperature and 1000°C, showed reactions in the slag at temperatures below 600°C. Synthetic samples containing variable proportions of alumina, silica, iron, calcium and potassium oxides were prepared and sintered at high temperature. The results show that the phases present are identical to the slag samples. Synthetic samples richer in CaO content tend to melt at a lower sintering temperature, ascribed to the formation of calcium aluminosilicate.

Viscosity measurements were conducted on three slag samples at temperatures ranging from 1400 to 1700°C. The results show that viscosity is sensitive to compositional variation. As the SiO_2/Al_2O_3 mass ratio increases, viscosity decreases at a constant temperature. Using the formula proposed by Watt and Fereday (11), the viscosities of the present samples were calculated; the calculated values are higher than the measured values by multiples of 2 to 11.

RECOMMENDATIONS

The viscosity measurements of the slags suggest that the calculated viscosity data are not applicable to the western Canadian coal ashes. An extension of the present work to include the viscosity measurements of a wide range of slag compositions is required to develop a better equation to fit coal ashes of Canadian origin.

ACKNOWLEDGEMENTS

The writers wish to express gratitude to R. Prokopuk and H. Whaley of the CCRL, CANMET, for supplying the slag samples for this investigation. We also wish to extend our thanks to L.C. Janke of the Coal Laboratory for providing the chemical analyses of the slags and to the staff of the Mineral Sciences Laboratories for their assistance.

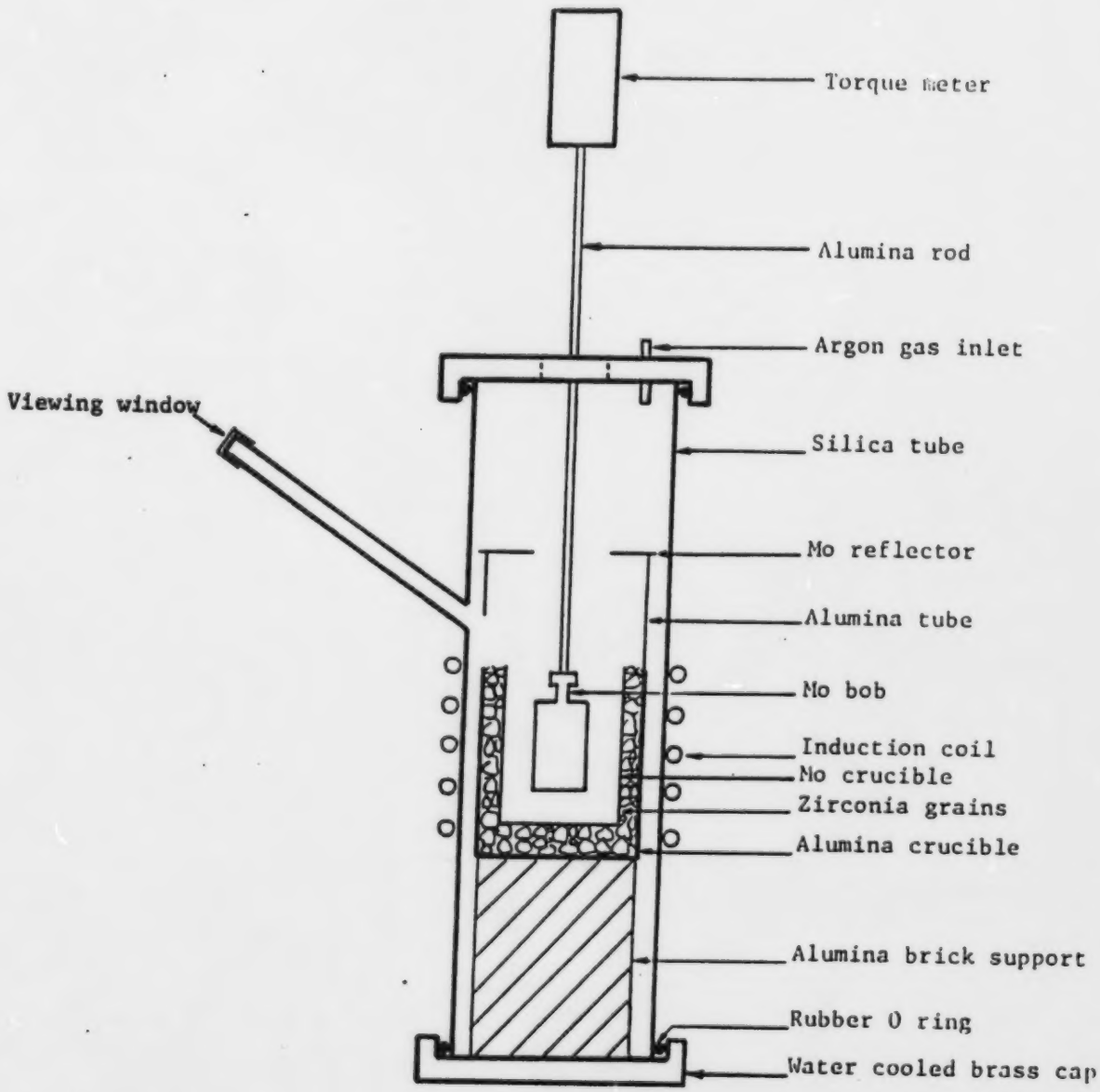

Fig. 1 - Schematic arrangement of viscometer and furnace set-up for viscosity measurement

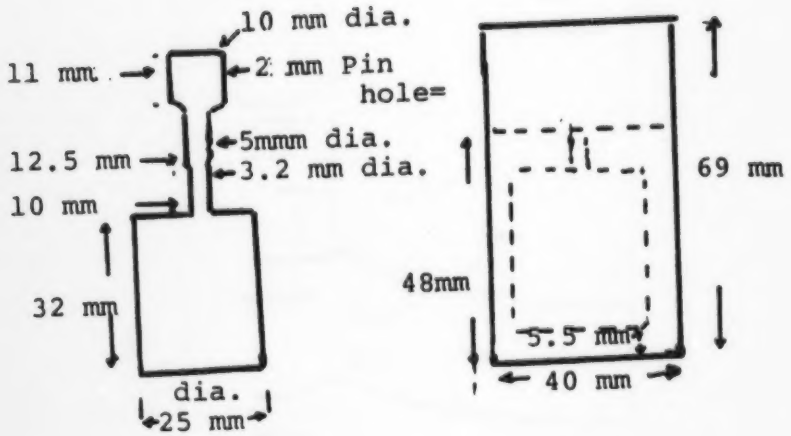

Fig. 2 - Concentric cylinder viscometer

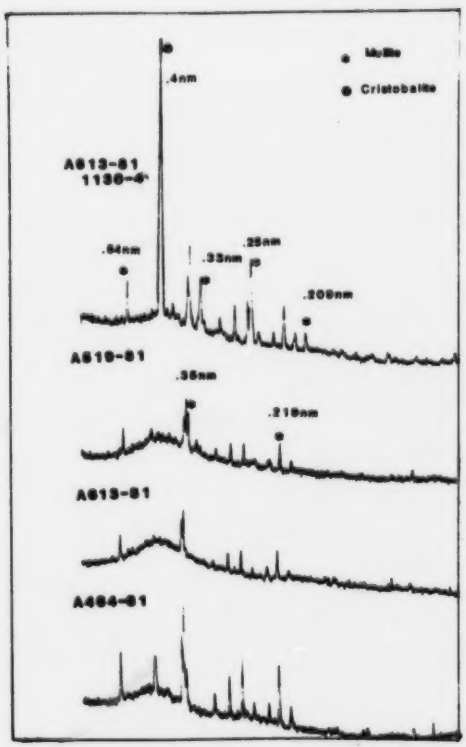

Fig. 3 - XRD patterns for the slag samples and slag sample heat treated (A613-81-1130-4)

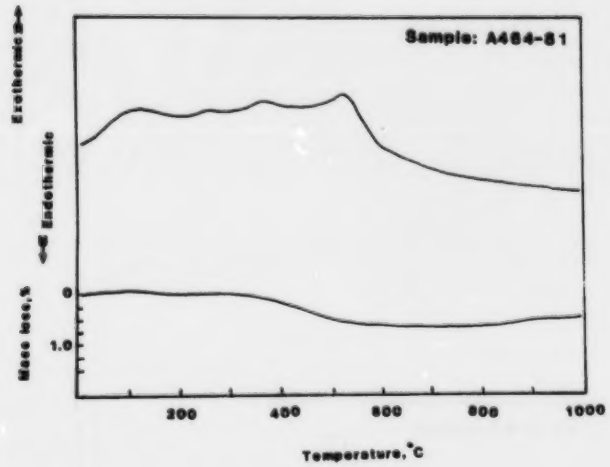

Fig. 4 - DTA and TGA thermograms for slag sample A464-81

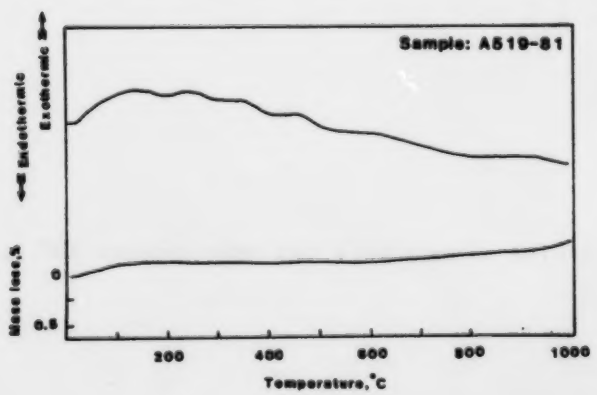

Fig. 5 - DTA and TGA thermograms for slag sample A519-81

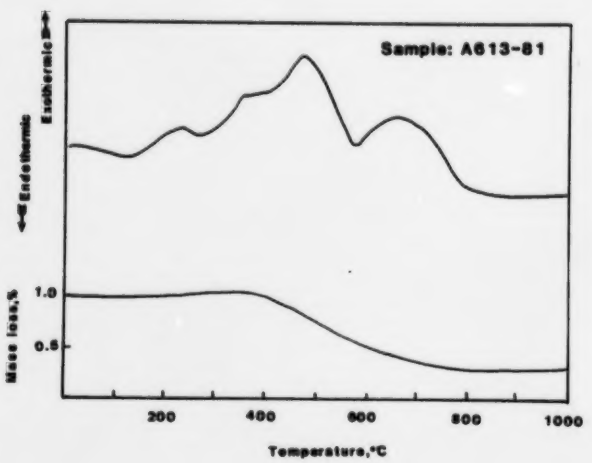

Fig. 6 - DTA and TGA thermograms for slag sample A613-81

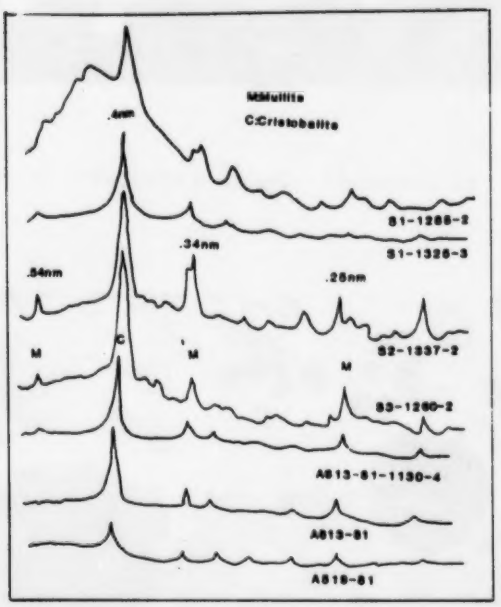

Fig. 7 - XRD patterns for the as-received slag samples (A613-81 and A-519-81), heat treated slag sample (A613-81-1130-4) and synthetic samples (S1-1285-2, S1-1235-3, S2-1337-2 and S3-1260-2)

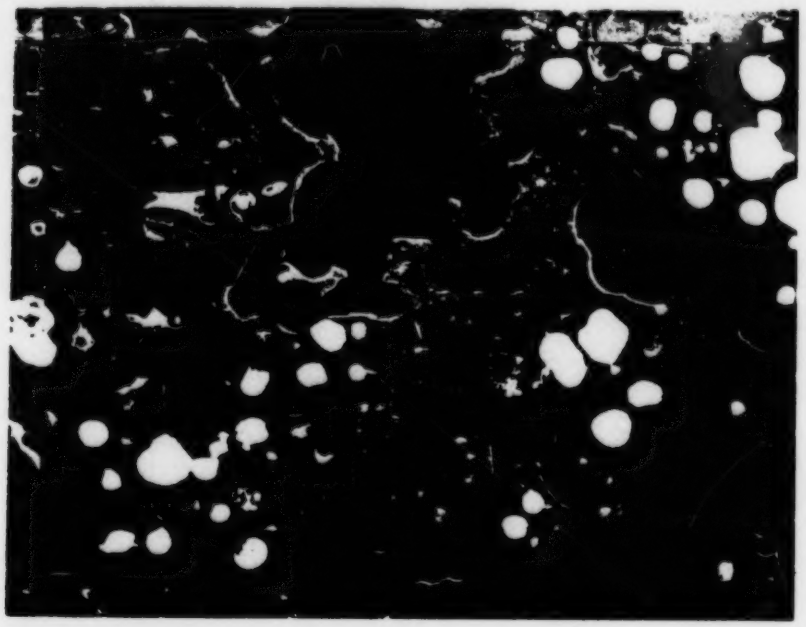

Fig. 8 - SEM micrograph of synthetic sample sintered at 1377°C for 2.5 h

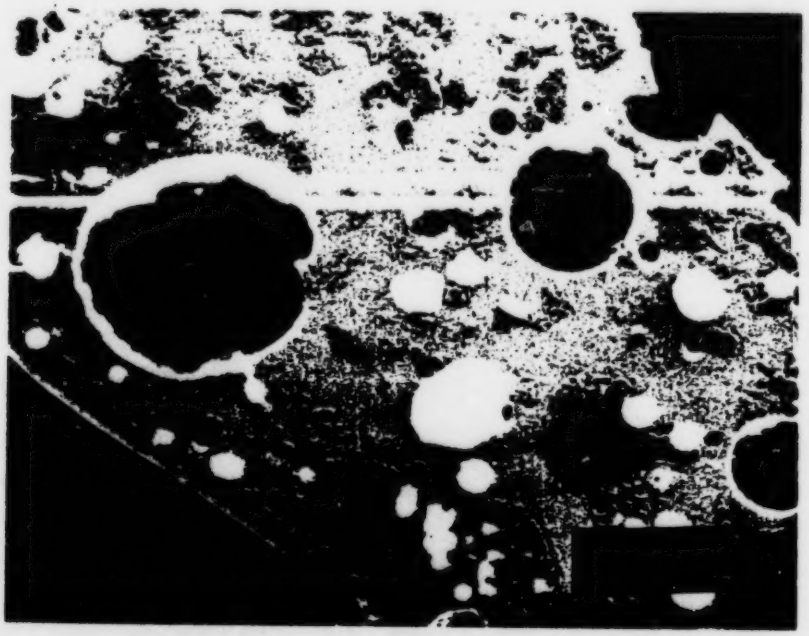

Fig. 9 - SEM micrograph of synthetic sample sintered at 1390°C for 2.5 h

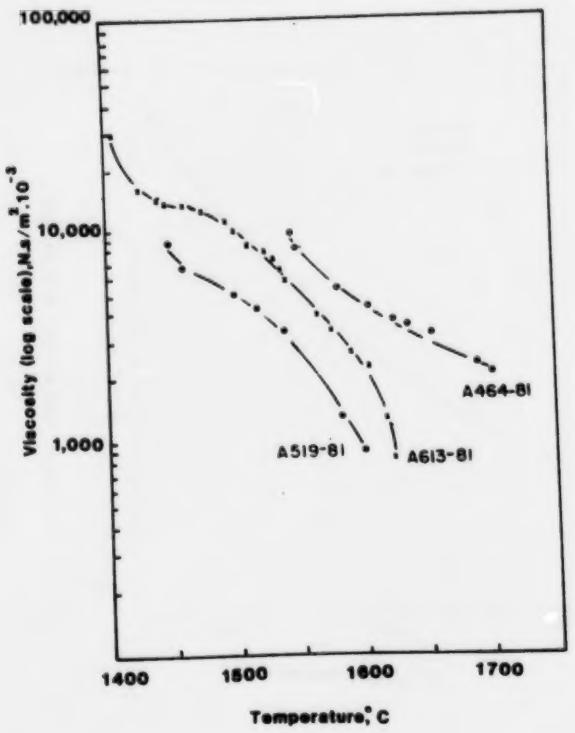

Fig. 10 - Viscosity as a function of temperature for the slag samples

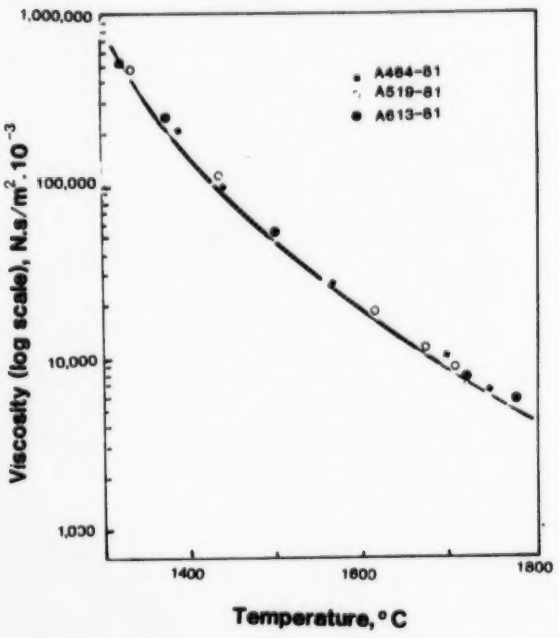

Fig. 11 - Calculated viscosity-temperature relationship for the slag samples

Table 1. Chemical composition of the slag samples

Oxide	Sample no.											
	A464-81		A484-81		A519-81		A613-81		A592-81		A571-81	A545-81
	+	*	+	*	+	*	+	*	+	*	+	+
SiO_2	58.84	60.0	58.31	60.4	61.63	62.6	52.23	67.5	61.79	64.4	59.41	62.67
Al_2O_3	28.73	29.5	29.42	27.7	23.45	20.6	20.58	21.9	23.29	23.4	29.98	23.14
Fe_2O_3	2.83	2.3	2.33	2.4	6.57	6.6	3.02	2.2	2.87	4.3	2.36	5.87
TiO_2	1.45	1.8	1.5	1.6	0.96	1.2	0.94	0.8	0.97	0.9	1.35	0.51
P_2O_5	0.50	n.a.	0.64	0.7	0.96	0.9	0.42	n.a.	0.33	n.a.	0.77	0.51
CaO	2.74	3.0	2.54	2.9	2.05	1.3	2.98	2.6	3.33	2.9	2.86	1.70
MgO	0.70	1.1	0.58	1.0	1.16	1.4	0.96	2.6	1.26	2.9	0.77	1.13
K_2O	n.a.	1.6	n.a.	2.4	n.a.	4.6	n.a.	1.4	n.a.	3.0	n.a.	n.a.
Na_2O	0.10	n.a.	0.11	n.a.	0.08	n.a.	0.71	n.a.	0.76	n.a.	0.14	0.09
BaO	0.35	0.5	0.53	0.7	0.60	0.6	1.13	0.6	0.95	0.3	0.96	0.93
SrO	0.39	n.a.	0.11	n.a.	0.08	n.a.	0.12	n.a.	0.10	n.a.	0.20	0.26
SO_3	0.30	n.a.	0.01	n.a.	0.20	n.a.	0.01	n.a.	0.14	n.a.	0.01	0.01
LOI	0.70	n.a.	5.40	n.a.	0.10	n.a.	16.00	n.a.	5.00	n.a.	0.30	0.20

+ Analyses supplied by Coal Chemistry Laboratory of ERL, CANMET
* Analyzed by Electron microprobe
n.a. = not analyzed

Table 2. Thermal behaviour of slag samples determined by the ASTM testing method

Sample no.	Oxidized condition				Reduced condition			
	temp, °C							
	I.D.	S	H	F	I.D.	S	H	F
A464-81	1483+	+	+	+	1483+	+	+	+
A484-81	1483+	+	+	+	1483+	+	+	+
A571-81	1483+	+	+	+	1483+	+	+	+
A592-81	1316+	1438	1482	+	1332	1421	1483+	+
A613-81	1343+	1468	1482	+	1311	1474	1482+	+
A519-81	1394+	1483	1483+	+	1341	1427	1482+	+
A545-81	1410+	1471	1482+	+	1341	1443	1482+	+

I.D. = initial deformation temperature

S = softening temperature

H = hemispheric temperature

F = fluid temperature

+ = above the stated temperature

Table 3. Chemical composition of the synthetic samples

Sample no.	Oxide, mass %				
	Al_2O_3	SiO_2	Fe_2O_3	CaO	K_2O
S1	31.2	61.8	3.0	2.0	2.0
S2	31.2	61.8	3.0	3.5	0.5
S3	31.2	61.8	3.0	2.5	1.5
S4	31.2	61.8	3.0	3.0	1.0

Table 4. Vicometer calibration equations

RPM	=A+BV($N.s/m^3 .10^3$) *		Approx viscosity range ($N.s/m^3 .10^3$)
	A	B	
1	-173	4624	935 to 5000
2.5	-68	1823	935 to 5000
5	-65	920	450 to 5000
10	-49	469	324 to 1500
20	-13	229	102 to 935
50	4	86	60 to 450
100	2	45	50 to 324

*A and B are constants; V is the voltage output of the torque meter in mV

Table 5. Phase characteristics of the slags

Sample no.	Major phase*	Minor-trace**	Sub-quantity***
A464-81	glass	mullite, cristobalite quartz, graphite	Fe_3O_4, Fe_2O_3, Al-Ca-Fe silicate
A484-81	glass	mullite, cristobalite quartz	Fe_3O_4, Fe_2O_3 Al-Ca-Fe silicate
A571-81	glass	mullite, cristobalite quartz, graphite	feldspar
A592-81	glass	mullite, quartz	Fe oxide, TiO_2, Mg-Al-Ca silicate, Ca-Al silicate
A613-81	glass	mullite, quartz	Fe_7Si_3
A519-81	glass	mullite, quartz	Fe oxide
A545-81	glass	mullite, quartz	

*phase identified by optical microscopy and XRD (amorphous)
**phase identified by XRD, EDXR/SEM
***phase identified by optical microscopy, EDXR/SEM, EMP

Table 6. Mass of silica, alumina and mass ratio of silica/alumina of the slag samples

Sample no.	SiO_2 Mass %	Al_2O_3 Mass %	$SiO_2 : Al_2O_3$ Mass ratio
A519-81	61.63	23.45	2.63
A613-81	52.23	20.58	2.54
A464-81	58.84	28.73	2.05

REFERENCES

1. Winegartner, E.C. and Rhodes, B.T. "An empirical study of the relation of chemical properties to ash fusion temperatures"; J Eng Power, Trans ASME Series A: 97:395-406; 1975.

2. Bryers, R.W. and Taylor, T.E. "An examination of the relationship between ash chemistry and ash fusion temperatures in various coal size and gravity fractions using polynomial regression analysis"; Trans ASME 108:528-539; 1976.

3. Huggins, F.E., Kosmack, D.A. and Huffman, G.P. "Correlation between ash-fusion temperatures and ternary equilibrium phase diagrams"; Fuel 60:577-584; 1981.

4. Bryers, R.W. "Influence of the distribution of mineral matter in coal on fireside ash deposition", Trans ASME 101:506-515; 1979.

5. Toguri, J.M., Kaiura, G.H. and Marchant, G. "The viscosity of the molten $FeO-Fe_2O_3-SiO_2$ system"; Extractive Metallurgy of Copper; 1: 259-273; Port City Press; 1976.

6. Van Wazer, L.R. Lyons, J.W., Kim, K.Y. and Colwell, R.E. "Viscosity and fluid measurements"; Interscience, New York; 1963.

7. Chen, T.T., Quon, D.H.H. and Wang, S.S.B. "Phase characteristics and microstructures of seven furnace slag deposits from a utility boiler fired with Western Canadian coals"; Division Report ERP/MSL 83-12 (TR); CANMET, Energy, Mines and Resources Canada; 1983.

8. Sage, W.L. and McIlroy, J.B. "Relationship of coal-ash viscosity to chemical composition"; J Eng Power 145-155; April, 1960.

9. Nicholls, P. and Reid, W.T. "Viscosity of coal slags; Trans ASME 62:141-153; 1940.

10. Reid, W.T., Cohen, P. "The flow characteristics of coal-ash slags in the solidification range"; Trans ASME 66:83-97; 1944.

11. Watt, J.D. and Fereday, F. "The flow properties of slags formed from the ashes of British coals: Part 1. Viscosity of homogeneous liquid slags in relation to slag composition"; J Inst Fuel 42:99-103; 1969.